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Surface extraction algorithm influence on the uncertainty assessment and tolerance compliance of computed tomography measurements

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Abstract

Computed tomography (CT) is progressively assuming an important role in metrology. However, many challenges still remain, especially regarding its measurement uncertainty calculation and, therefore the tolerance compliance. This is even more challenging when it is applied to complex parts, including parts with complex geometries or multi-material parts. In those cases, the use of different surface extraction algorithms may have an important influence in the final measurement result. This paper presents the experimental analysis carried out on two parts with a variety of geometries, one with regular geometries and another one with freeform surfaces. In all the cases two surface extraction algorithms have been applied: one based on threshold and another one on gradient methods. The measured values and the estimated uncertainties are eventually analyzed together with the micro manufacturing tolerances compliance and the U/T ratios are calculated, showing the influence of using different surface extraction algorithms.

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Keywords: Micro-computed tomography; Uncertainty; Tolerance

1. Introduction

In the field of manufacturing engineering, smaller mechanical parts are being more and more designed and produced. These micro-mechanical parts are characterized by dimensional tolerances to be verified in the micrometer down to the sub-µm range. This requires high accuracy metrological tools for process optimization with sub-µm measurement resolution and repeatability and with combined expanded uncertainty in the single-digit micrometer range. This challenge has been addressed by applying several contact and non-contact micro metrological techniques, such as tactile micro-coordinate measuring machines (µCMM) that can provide the required metrological performances [1,2], but are limited in terms of measuring capability because of some factors such as: accessibility and minimum measurable feature size due to the probe and stylus dimensions, relatively low measuring point density, relatively high measuring time, possible deformation of soft substrate materials due to the probing force. Non-contact measuring instruments based on optical techniques [3] (e.g., optical CMM [4], confocal and focus variation microscopes [5], coherence scanning interferometers [6], etc.) are capable of meeting the metrological requirements, but have also limitations both in measuring vertical walls and high aspect ratio structures, and accessing out-of-sight features. In addition, both contact and non-contact techniques share a further limitation: they are not able to measure inaccessible internal features.

To meet these demands new technologies based on new measuring concepts are being developed. One of them that can be a viable solution to the limitations mentioned before is the use of micro-Computed Tomography (µCT or micro-CT) for

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geometrical coordinate measurements [7]. This is a non-contact imaging technique that can provide a densely populated 3D scanning point cloud of an object, allowing the measurements of both external and otherwise non-accessible internal structures and features. Micro-CT metrology techniques are more and more applied for the geometrical verification of micro-parts [8,9]. Great efforts are being made for the complete acceptance of computer tomography for metrology purposes, especially because of the numerous and complex factors which influence the µCT performance [10], and the lack of accepted test procedures and standards. Both limitations are directly related to the measurement uncertainty evaluation, needed to perform a reliable establishment of traceability. In order to cope with this issue, a previous work was developed by the authors to provide an experimental approach for the uncertainty assessment of dimensional measurements using Computed Tomography at the mm and sub-mm scales [11]. In that work, an alternative method for the measurement uncertainty assessment of 3D complex geometries by using CT is presented. The method is based on the micro-CT system Maximum Permissible Error (MPE) estimation, determined experimentally by using several calibrated reference artefacts. This approach is used also in the present work.

One of the most critical and challenging steps in the CT measuring process is the surface extraction phase from the CT volume data. An incorrect determination of the surface affects directly the accuracy of dimensional measurements and, consequently, the measurement uncertainty. In a previous work, an edge detection method for the surface extraction based on a 3D Canny algorithm with sub-voxel resolution was presented as an alternative to the most commonly used technique nowadays, i.e. the local threshold definition [12]. In the present paper, these two surface extraction algorithms have been applied and compared: one based on threshold [13] and another one (3D Canny) based on gradient methods. An experimental analysis has been carried out on different micro-parts in order to analyze the influence of the surface extraction algorithm used on the uncertainty assessment and tolerance compliance. The aim is to probe if the Canny algorithm is also feasible with CT characterization of miniaturized three dimensional complex geometries with freeform surfaces, such as a dental file workpiece. This introduces an interesting innovation since, as explained in section 2, the 3D Canny algorithm is applied to the images along each of the three Cartesian directions, which has shown to be very effective for simple geometries, but has not been verified yet on complex geometries where the surfaces' vectors may be very different from those Cartesian directions.

2. Surface extraction algorithms

Two different algorithms were applied for the surface extraction to perform the measurements: one based on a local threshold method [12] (named CT1 from now on) and another one based on the 3D Canny algorithm [13] (named CT2). A previous comparative between both of them was carried out in [14] for a test part, showing that the local thresholding method is, in general, less repeatable, in contrast with the Canny algorithm, which shows high repeatability and, therefore, the possibility of being corrected. In the present work a more detailed comparative is carried out by using different parts and focusing on the uncertainty assessment and tolerance compliance of the measurements.

A brief description of both techniques is presented in the following sections.

2.1. Local threshold method (CT1)

Threshold method for surface extraction in CT is a well-known technique adapted from the 2D image segmentation. It is based on the determination of a gray value (called threshold) used to distinguish one material to the other. Voxels with higher gray value than threshold are considered belonging to the part, and voxels with lower value are considered as air (see Fig. 1). After that, sub-voxel techniques based on a local 3D interpolation are used to determinate the surface points.

2.2. Canny algorithm (CT2)

Developed by the authors and implemented in Matlab®, the named CT2 method is based on the 3D Canny algorithm and its methodology is divided into some steps as detailed in [13]. In summary, a Gaussian filter is applied to the images along each of the three Cartesian directions, using a 1x10 convolution mask oriented along the direction. After this phase, three different 3D images (X–Y, Y–Z and Z–X in Fig. 2a) are obtained, each showing the transition between materials along the corresponding direction. Later, an algorithm to calculate with sub-voxel resolution the XYZ-coordinates of the points in the area of the material transition is applied. This improves the actual spatial resolution of the edge detection method down to one hundredth of the voxel resolution. This refinement is carried out separately and independently along all the three XYZ directions obtaining the three different coordinates of each surface point (Fig. 2b). Finally, the measurement is carried out by using the point cloud of the part surface obtained from the previous step.

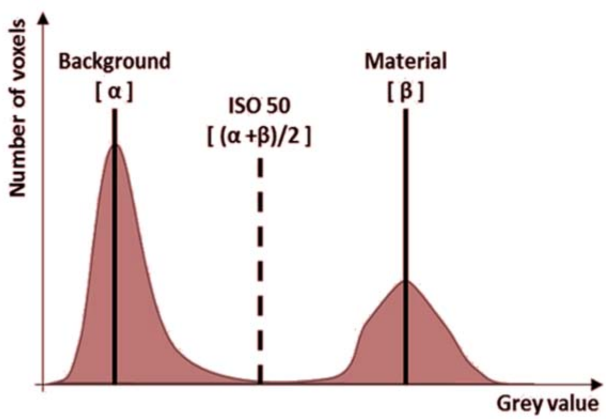

Fig. 1. Determination of the threshold value based on the ISO50 method

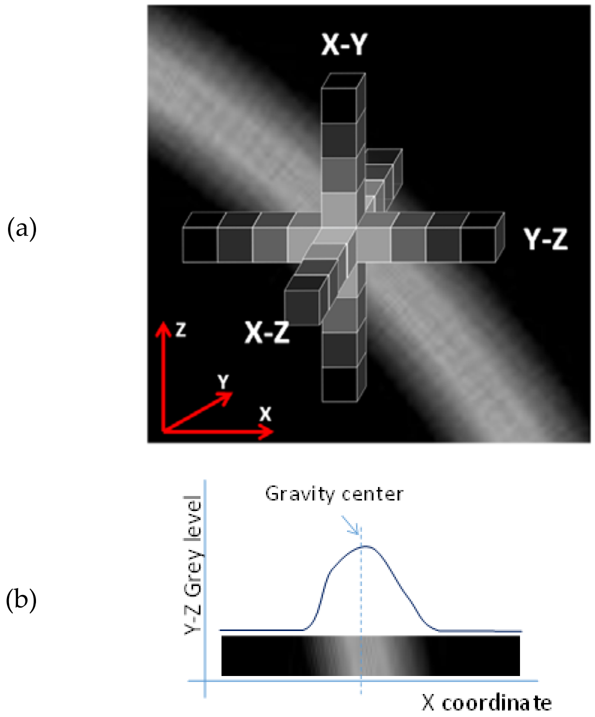

Fig. 2. Sub-voxel resolution refinement of the 3D Canny algorithm: (a) Scheme of the 3D refinement strategy; (b) Example -for the X coordinate- of the principle used to calculate the point after refinement

3. Materials and methods

Two parts made of different materials and with different geometries have been used for this study.

3.1. Dog bone workpiece

The first part is a miniaturized dog bone (Fig. 3). This specimen is made of acetal polyoxymethylene (POM) copolymer and used for micro mechanical material testing. In this case, five dimensions of four items (DB1, DB2, DB3 and DB4) were verified at both the left and the right sides of the part: lengths (L, a, b, c, d) and thicknesses (A, B, C, D, E, F), respectively (Fig. 3). Nominal dimensions are: lengths L = 11.80 mm; lengths a, c = 3.00 mm; lengths b = 1.50 mm; lengths d = 1.35 mm and thicknesses A to F = 1.00 mm. Table 1 summarizes all the parameters of the dog bone, their description, nominal values and tolerances.

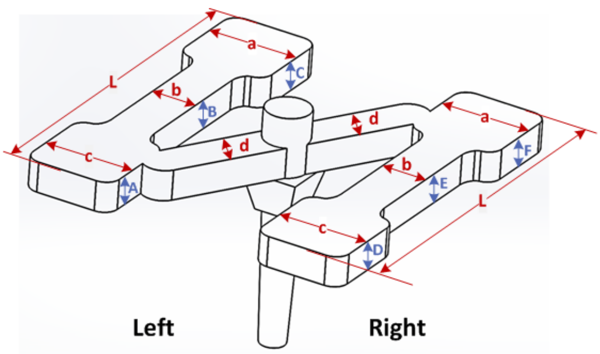

Fig. 3. Dog bone. Characteristic dimensions: left and right lengths (L, a, b, c, d) and thicknesses (A, B, C, D, E, F).

Table 1. Dog bone: measurands, description, nominal and tolerance values.

Measurand	Description	Nominal value	Tolerance
L	Length	11.80 mm	±0.03 mm
a, c	Length	3.00 mm	±0.03 mm
b	Length	1.50 mm	±0.02 mm
d	Length	1.35 mm	±0.02 mm
A, B, C, D, E, F	Thickness	1.00 mm	±0.02 mm

3.2. Dental file workpiece

A ProTaper F2 finishing file (produced by Dentsply Maillefer, York, PA, USA) is used for the study [15]. This instrument is manufactured in a Ni-Ti alloy. Its complex 3D geometry is defined by different dimensions of such root-canal instruments include lengths, diameters, helix angles and pitches. The dimensions to be verified are the following (see Fig. 4): (i) length of the active cutting part (La); (ii) variable diameter along the file length (Dn, n=0,1,2,…,13), being D0 the diameter at the file tip and D1, D2, D3, etc. the diameters at 1, 2, 3, etc. mm along the file axis respectively; (iii) helix angle (Hn, n=1,…,10) or the angle formed between the helix and the file axial axis, being the first one (H1) the angle formed between the tip and the base of the file; (iv) helix pitch (Pn, n=1,…,11) or the distance between a point in the forward edge and its corresponding point in the adjacent edge along the file longitudinal axis, being P1 the first helix pitch starting from the tip of the file.

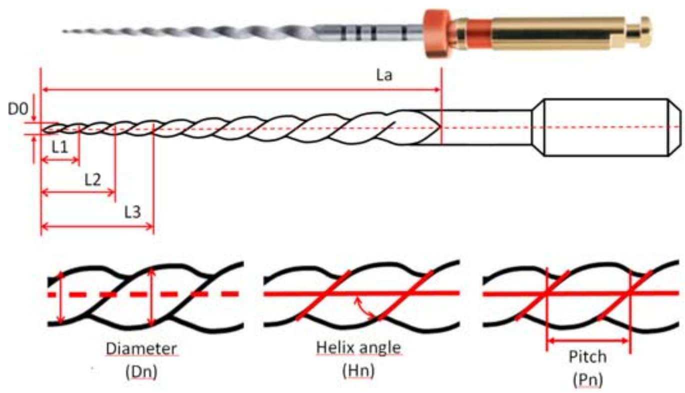

Fig. 4. Dental file and characteristic dimensions: length of the active cutting part (La); diameter (Dn); helix angle (Hn); pitch (Pn).

The nominal dimensional values available for this dental file are: a cutting segment (La) of 16 mm in length, a tip diameter (D0) of 0.25 mm, a fixed conicity of 8% between D0 and D3 and a variable conicity from D3 to D13 along its axis. There are only specified tolerances for diameters and length. Table 2 summarizes all the parameters of the dental file, their brief description, nominal values and tolerances.

Table 2. Dental file: measurands, nominal and tolerance values.

Measurand	Nominal value	Tolerance
La	16 mm	±0.5 mm
Dn (n=0,…,13)	D0=0.25 mm to D6	±0.02 mm
	D7=0.60 mm to D13	±0.04 mm

3.3. Micro-CT system

A General Electric eXplore Locus SP cone-beam micro-CT machine was used for the CT measurements of both parts. Its X-ray source voltage range is between 50 and 90 kV, the maximum resolution or minimum voxel size of 8 µm and a cylindrical working volume of 44 mm in diameter and 56 mm in height. During the scanning the temperature was recorded inside the machine, obtaining a temperature range of 20±2ºC. The scanning parameters used for the measurement of the four dog bones were: voltage = 80 kV, intensity = 95 µA, increment angle = 0.4 degrees and voxel size = 8 µm. The dental file measurements were performed with the following parameters: voltage = 90 kV, intensity = 80 µA, increment angle = 0.4 degrees and voxel size = 28 µm.

4. Results and discussion

The measurement uncertainty has been evaluated according to ISO 14253-2:2011 [16] as follows:

$$U_{95,CTi} = k\sqrt{u_r^2 + u_p^2 + u_w^2 + u_b^2} \qquad (1)$$

The term k is the coverage factor (k=2) and i-index considers the local threshold method (CT1) or Canny algorithm (CT2). This expression allows the determination of the measurement uncertainty in any case, even when a previous calibration of the analyzed workpiece -or a workpiece with similar geometric characteristics- with a more precise measurement system is either not available or it is simply not possible. On the other hand, it requires having the maximum permissible error (MPE) of the CT system previously determined in order to calculate u_r [17]. Finally, u_p is the standard uncertainty of the measurement procedure (n=10 repeated measurements), u_w is the standard uncertainty from the material and manufacturing variations, and u_b is the standard uncertainty associated with the residual systematic error of the measurement process.

A tolerance verification capability analysis is performed in order to verify whether the measured components are within the specifications and whether the CT system has a sufficiently low measuring uncertainty so that it is suitable for tolerance verification in micro manufacturing. This is demonstrated by evaluating the 2U/T ratio (where U = expanded uncertainty of the CT measurement and T = tolerance of a certain measurand as specified in the component design) as an indicator of the system measuring capability.

4.1. Dog bone results

The uncertainty results obtained for the expanded uncertainty (U_{95} with a coverage factor k=2) are presented in Table 3. Due to the almost equivalent results of the four specimens measured, only DB1 results are included. Three measurands have been selected as representative from the entire workpiece: L left, a left and E thickness (see Fig. 3). The results from the two surface extraction techniques, CT1 and CT2, are also compared. As can be observed the uncertainty values are slightly higher when using the CT1 algorithm.

Table 3. Dog bone (DB1): Uncertainty contributors and expanded uncertainty (U_{95}, k=2) obtained by the CT system with both surface extraction techniques.

Measurand (DB1)	L left [µm]		a left [µm]		E thickness [µm]	
Technique	CT1	CT2	CT1	CT2	CT1	CT2
U_{95}	9.9	9.7	8.1	7.9	7.9	7.5

The relation between the nominal value and tolerance limits (see Table 1), measured value and uncertainty range is presented in Fig. 5 for both CT1 and CT2 algorithms and for the four specimens (DB1, DB2, DB3 and DB4).

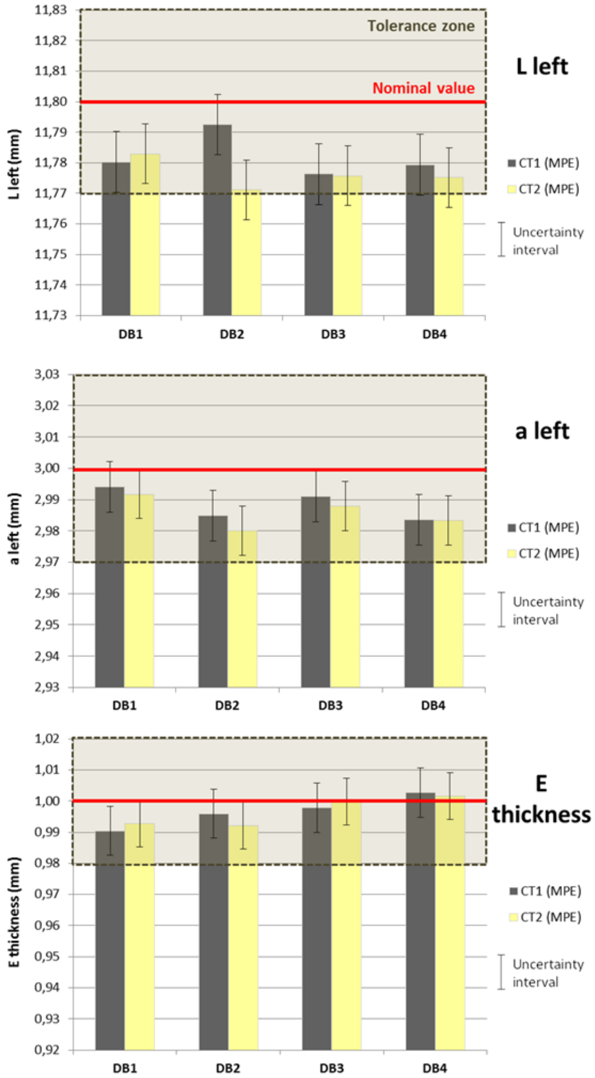

Fig. 5. Dog bone: Measurement results of the four workpieces and selected measurands obtained using two surface extraction techniques (CT1, CT2). L left (up and left); a left (up and right); E thickness (down and right).

For effective tolerance verification the 2U/T ratio must be lower than 40% when the tolerances are tight, as in the case of micro-manufactured products [4,26]. In this case, all the measurands meet with this rule for both CT1 and CT2 surface extraction techniques.

4.2. Dental file workpiece

The results of the measurement uncertainty obtained for the dental file are shown in Table 4. The maximum expanded uncertainty (U_{95}, k=2) obtained by both CT1 and CT2 are shown for some selected dimensions of the dental file (D11, La) as a representation of those with dimensional tolerances associated.

As can be observed the uncertainty values are again slightly higher when using the CT1 algorithm. This is mainly due to the contribution of the systematic error in the final uncertainty calculation. Generally, 3D Canny algorithm concludes in more accurate results and, therefore, in a lower systematic error.

Table 4. Dental file: expanded uncertainty (U_{95}, k=2) obtained by the CT system with both surface extraction techniques used

Measurand	La [µm]		D11 [µm]	
Technique	CT1	CT2	CT1	CT2
U_{95}	11.3	10.3	9.8	7.5

Tolerance specifications are only defined for the length of the active cutting part (La) and variable diameters (D0 to D13). The results of the ratio 2U/T for them are summarized in Table 5. For the active length, with a wider tolerance, the two techniques meet the requirement. It can be observed that the ratio obtained with the OCMM for the diameters and the active length is always smaller than 0.4 (see also Figure 10). In the case of CT1 and CT2 measurements, for dimensions from D0 to D6, where the tolerances are smaller, the percentage number of measurements with a ratio $2U/T \leq 0.4$ is slightly above 57% and 71%, respectively. In contrast, for dimensions from D7 to D13, where the tolerances are larger, the relationship $2U/T \leq 0.4$ is achieved by around 85% dimensions with CT1 and 100% dimensions with CT2. Therefore, despite higher uncertainties and challenges in performing CT scanning metrology, its applicability towards tolerance verification on complex geometries appears promising.

Table 5. Dental file: Percentage of $2U/T \leq 0.4$ values calculated for all CT measurements and obtained by using the two surface extraction techniques (CT1, CT2).

Measurand	CT1	CT2
La	100%	100%
D0 to D6	57.1%	71.4%
D7 to D13	85.7%	100%

5. Conclusions

In this paper a comparative analysis of two surface extraction techniques in computed tomography has been presented for the case study of two different micro-parts. Considering systematic errors results, it was found that the edge detection technique CT2 (3D Canny) compared to the CT1 (local thresholding) provides an edge definition with lower systematic errors and, therefore, less dependent on the geometry of the measured part. The uncertainty results do not show a clear difference between both techniques, although slightly lower measurement uncertainty results have been observed for CT2 (3D Canny) than for CT1 (threshold) due to higher repeatability, especially when the tolerance verification has been analyzed. The 3D Canny technique allows for an improved distinction and determination of the edges, which has shown to be adequate for the measurement of complex geometries as the one analyzed in this research for the dental file.

In conclusion, these results make consider µCT as a measuring technique with high potential for off-line quality control of micro-parts. In addition, the reduction in the scanning time can turn in-line quality control into a real possibility in the near future. Indeed, CT has the possibility to overcome some of the limitations of, e.g., OCMMs, such as their problems in providing accurate measurements of non-cooperative surfaces, or their limited accuracy when measuring along the vertical axis.

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References

[1] Claverley JD, Leach RK. (2015) A review of the existing performance verification infrastructure for micro-CMMs. *Precision Engineering* 39:1–15.

[2] Bos EJC. (2011) Aspects of tactile probing on the micro scale. *Precision Engineering* 35:228–240.

[3] Hansen HN, Carneiro K, Haitjema H, De Chiffre L. (2006) Dimensional micro and nano metrology. *CIRP Annals - Manufacturing Technology* 55(2):721–743.

[4] Tosello G, Hansen HN, Gasparin S. (2009) Applications of dimensional micro metrology to the product and process quality control in manufacturing of precision polymer micro components *CIRP Annals - Manufacturing Technology* 58(1):467–72

[5] Mueller T, Jordan M, Schneider T, Poesch A, Reithmeier E. (2016) Measurement of steep edges and undercuts in confocal microscopy. *Micron* 84:79–95.

[6] Henning A, Giusca C, Forbes A, Smith I, Leach R, Coupland J, Mandal R. (2013) Correction for lateral distortion in coherence scanning interferometry. *CIRP Annals - Manufacturing Technology* 62(1):547–550.

[7] Kruth JP, Bartscher M, Carmignato S, Schmitt R, De Chiffre L, Weckenmann A. (2011) Computed tomography for dimensional metrology. *CIRP Annals - Manufacturing Technology* 60(2):821–842.

[8] Ontiveros S, Yagüe-Fabra JA, Jiménez R, Tosello G, Gasparin S, Pierobon A, Carmignato S, Hansen HN. (2012) Dimensional measurement of micro-moulded parts by computed tomography. *Measurement Science and Technology* 23(12):125401

[9] Möhring H-C, Kersting P, Carmignato S, Yagüe-Fabra JA, Maestro M, Jiménez R, Ferraris E, Taner Tunc L, Bleicher F, Wits WW, Walczak K, Hedlind M. (2015) A testpart for interdisciplinary analyses in micro production engineering. *Procedia CIRP* 28:106-112.

[10] Andreu V, Georgi B, Lettenbauer H, Yague JA (2009) Analysis of the error sources of a Computer Tomography Machine. *Proceedings of Lamdamap conference* 462-471

[11] Jiménez R, Torralba M, Yagüe-Fabra JA, Ontiveros S, Tosello G. (2017) Experimental Approach for the Uncertainty Assessment of 3D Complex Geometry Dimensional Measurements Using Computed Tomography at the mm and Sub-mm Scales. *Sensors* 17:1137

[12] Yagüe-Fabra JA, Ontiveros S, Jiménez R, Chitchian S, Tosello G, Carmignato S. (2013) A 3D edge detection technique for surface extraction in computed tomography for dimensional metrology applications. *CIRP Annals - Manufacturing Technology* 62(1):531–534

[13] Jiménez R, Ontiveros S, Carmignato S, Yagüe-Fabra JA. (2013) Fundamental correction strategies for accuracy improvement of dimensional measurements obtained from a conventional micro-CT cone beam machine. *CIRP Journal of Manufacturing Science and Technology* 6(2):143-148

[14] Ontiveros S, Yagüe JA, Jiménez R, Brosed F. (2013) Computer Tomography 3D edge detection comparative for metrology applications. *Procedia Engineering* 63:710–719

[15] Ruddle CJ. (2001) The ProTaper endodontic system: geometries, features, and guidelines for use. *Dentistry Today* 20:60–67.

[16] ISO 14253-2:2011. (2011) Geometrical product specifications (GPS). Inspection by measurement of workpieces and measuring equipment. Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification.

[17] Müller P, Hiller J, Cantatore A, De Chiffre L. (2012) A study on evaluation strategies in dimensional X-ray computed tomography by estimation of measurement uncertainties. *International Journal of Metrology and Quality Engineering* 3:107–115.